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13. ABSTRACT (Maximum 200 words)

The major technical accomplishments for the development of a mesoscale catalytic combustor to be coupled with direct energy conversion modules for electric power production are summarized. Most importantly, clean and efficient combustion of complex hydrocarbon mixtures, such as the notoriously problematic JP8, has been accomplished. Using gas chromatographic analysis of the exhaust gases, a combustion efficiency on the order of 99% is estimated. The device was successfully coupled to a free piston Stirling engine in preliminary experiments. In addition, fundamental studies were pursued on liquid fuel dispersion by the electrospray technique with both conventional manufacturing techniques and microfabrication, on the chemical kinetics of JP-8 surrogates and on the development of advanced laser diagnostics for JP-8 combustion systems.

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**Statement of the problem**

An attractive route to small-scale power generation is to exploit the large power density offered by liquid fuels, up to two orders of magnitude larger than the best batteries available on the market today. Practical considerations dictate that energy conversion be achieved by adapting the same, inexpensive, and ubiquitous logistic fuel supply, that is, liquid hydrocarbons such as JP-8. As part of a science and technology development program sponsored by the DARPA Palm Power program, a research group lead by Yale University, with a subcontract to Precision Combustion Inc. (North Haven, CT) (PCI), was given the task of developing a mesoscale JP-8 combustor. The Yale/PCI approach rested on the merging of two technologies: the electrospray and a catalytic reactor design (patent pending). Before summarizing the principal results, we descrfibe briefly the two technologies.

Unlike most spray systems, that are tailored to relatively large flow rates and are poorly suited to miniaturization, the electrospray (ES) is ideally suited for small-scale combustion. The ES operates as follows: a conducting liquid emerging from the tip of a capillary tube is charged to a sufficiently high potential with respect to a ground electrode a short distance away, so that the liquid meniscus takes the shape of a cone from the tip of which a thin liquid thread emerges, in the so-called cone-jet mode [1]. This microjet breaks into a stream of charged droplets, which eventually spread to form a spray, more properly, an electrospray. Among the key features distinguishing the electrospray from other atomization techniques are: quasi-monodispersity of the droplets; Coulombic repulsion of the charged droplets, which induces spray self-dispersion, prevents droplet coalescence and enhances mixing with the oxidizer; and the use of a spray nozzle with a bore orders of magnitude larger than the size of the generated droplets, so that fuel line obstruction risks are minimized. Parasitic losses associated with the use of high voltage are minimal, since the power drawn by the electrospray is a negligible fraction of the generated power, even at modest conversion efficiency.

Once vaporized, the fuel is then burned catalytically, to ensure that CO to $CO_2$ conversion is completed in as a short a residence time as possible. This approach was implemented in the combustor by incorporating a compact reactor design based on the use of a series of PCI catalyst coated metal grids (Microlith®) [2]. The grids are stacked serially, each with short channel lengths, high cell density and low thermal mass. The resulting reactor is very compact, has rapid transient response and high energy density, and requires small amounts of precious metal catalysts. Catalyst formulations have been selected from platinum group metals and an alumina washcoat with appropriate additives. The advantages of this design stem from the reduction in mass transfer limitations, as compared to conventional monoliths having relatively thick boundary layers. Also, under conditions of chemical kinetic control, the particular design can pack more active area into a small volume, which means that insertion of such catalysts in a flow can provide more effective fuel conversion for a given pressure drop.

**Milestones of burner development**

1. Development of a clean and efficient burner, capable of converting in excess of 99% of the parent hydrocarbon to $CO_2$ and $H_2O$, with virtually no CO emission and less than 10 ppm of the parent hydrocarbon, despite the use of the notoriously problematic JP-8;
2. Demonstrated durability of the system in tests showing no evidence of catalyst deterioration after 500 hours of operation and modest maintenance requirements of the atomizer every 75 hrs;
3. Resistance to coking or fouling for several hours, even after preheating the gas to as high a temperature as 750 K, to mimic extensive exhaust heat recuperation;
4. Geometric versatility, as demonstrated by the development of planar, cylindrical and toroidal configurations to be tailored to potential candidates for the thermal-to-electric energy conversion;
5. Demonstrated scalability, with the toroidal configuration operated at as much as 1 $KW_t$ (thermal);
6. Interfacing the toroidal combustor with a Stirling engine, resulting in the generation of 44 $W_e$.

A schematic of a planar Yale/PCI burner and a picture with the glowing catalyst in operation is shown in Fig. 1. To maintain the volume for fuel evaporation and mixing to a minimum, it is advantageous to minimize the dimensions of the generated droplets, so that their evaporation time, scaling with the square of this dimension, would decrease, and so would the characteristic length scale over which full evaporation takes place. To that end, the total flow rate for a given thermal power level is dispersed into multiple electrospray sources, which in the present embodiment of the Yale/PCI combustor radiate from a common source (typically a 1/8 in., virtually unobstructable metal tube). Currently, the volume of the combustor has been reduced to about 10 cc, with a weight of approximately 20 g for the generation of 100-200 $W_t$.

To produce electric power from JP-8 using the combustion route, the Yale-PCI team coupled the combustor with a Stirling engine. The Stirling engine is the darling of thermodynamicists. Its potential rests on the fact that of all thermodynamic cycles on which heat engines are based, the Stirling can produce the highest efficiency, on the order of 55% of the (Carnot) theoretical maximum. The Stirling system is an external combustion engine in which the working fluid, typically helium, shuttles back and forth between a cold end and a heated end in a sealed container. The free-piston Stirling engines are designed for hermetically sealed operation in which no maintenance is necessary and the only moving part, the free piston, never comes in direct contact with the environment (e.g., dirt, sand, humidity) in which it operates. High efficiency and maintenance free operation are key factors that make this technology particularly appealing for power generation in the harsh environments for which the DARPA Palm Power program was conceived.

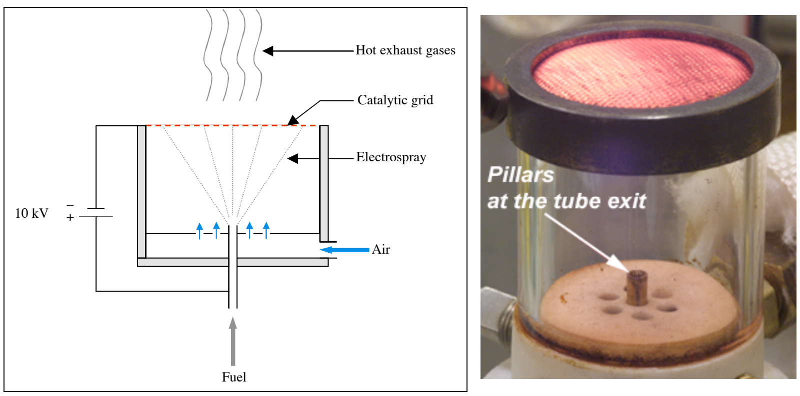


**Figure 1**

The Yale-PCI team initiated contact with the two leading manufacturers of free piston engines in the U.S.: STC (Kennewick, WA) and Sunpower Inc. (Athens, OH). A collaboration with STC lead to the development of a compact, toroidal combustor for the STC RG-55 Stirling engine. A week of tests in November 2003, in which the JP-8 combustor was coupled with the 55 $W_e$ generator, showed the promise of the approach and, without any effort to optimize coupling efficiency, culminated in generation of 44 $W_e$, as reported above. To our knowledge, this may be the first instance in which electric power has been obtained from JP-8 cleanly. The burner was operated for ten hours, three of which coupled with the engine. Yet, after it was disassembled, no apparent coking or deposit was observed on visual inspection. Furthermore, the burner did not appear to be affected by vibrations. These results are encouraging and show that the two technologies, electrospray catalytic combustor and Stirling engine, can be matched successfully.

**Other important results**

As appropriate for a science and technology program, various fundamental issues were addressed in ancillary studies leading to peer-review publications. They include:

1. The development and validation of a semi-detailed JP-8 chemical kinetic model, was investigated. The model was incorporated in detailed computational models of diffusion and premixed flames, with the ultimate goal of reducing the chemical kinetic mechanism to render it suitable for complex CFD models of practical combustion systems.
2. The development of a diagnostic technique based on two-color laser induced fluorescence from fluorescence tags added to the fuel, which allows for the measurements of both equivalence ratio (fuel/air mixing) and temperature in planar “slices” through the combustor.

3. The development of a novel approach to multiplexing based on a well-known, but hitherto unexploited, regime of operation, the multi-jet mode. Ordinarily, such a mode is rather unsteady and the range of flow rate at which appreciable multiplexing is achieved is small. However, if the multijet mode is anchored by some sharp features (e.g., grooves, ridges, etc.) machined at the outlet of the atomizer, to intensify the electric field at discrete points around its perimeter, then the cone-jets are simultaneously anchored at these features and a stable mode of operation is identified over several hundreds of volts and a broad range of flow rates. Most importantly, so long as the machining is precise, droplets generated do not vary significantly in size from spray to spray. As a result, a compact, inexpensive and versatile multiplexing system is realized without sacrificing droplet monodispersity.
4. The development of multiplexed electrospray distributors in Si by Deep Reactive Ion Etch (DRIE). The process allows for easy variation and scaling of nozzle and array design to optimize the intended application. The reproducibility of geometric features from protrusion to protrusion is a very important feature that ultimately favors microfabrication techniques with respect to conventional machining. It is, in fact, a prerequisite to equidistribution of flow rates among the multiplexed nozzles and to the establishment of a controlled electric field at each nozzle, that would in principle lead to the generation of identical sprays. The electrode configuration allows for the decoupling, to some extent, the electrospray forming region from the spray utilization region further downstream. To that end, we implemented a ring extractor configuration in which the microfabricated Si distributor is charged at about 1KV with respect to a grounded metal ring extractor plate positioned only 200 $\mu$m away by means of an insulator spacer. The ring extractor itself was designed and microfabricated using photolithography and metal etching to tolerances compatible with the microfabricated nozzle array. Remarkably, the system worked stably without problems. Modeling of the electric field using Femlab for a prescribed equipotential cone-jet liquid-gas interface shows that, as anticipated, the local electric field is such that each electrospray is independent of the other. A simple explanation of this observation rests on the small (submillimeter) distance between the cylindrical protrusions of the microfabricated plate and the extractor ring. Such a length scale is smaller than the nozzle to nozzle separation. As a result, there is no "cross-talk" among the electrosprays.

Progress in the program was documented in 7 peer-reviewed articles [3-9], a patent application [10], some conference proceedings [11-18] and a number of reports posted on the DARPA Palm Power Website (http://palmpower.walcoff.com).

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